



A Review of Distributed Electric Propulsion Concepts for Air Vehicle Technology

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AIAA / IEEE Electric Aircraft Technologies Symposium (EATS)
Cincinnati, Ohio

July 12, 2018

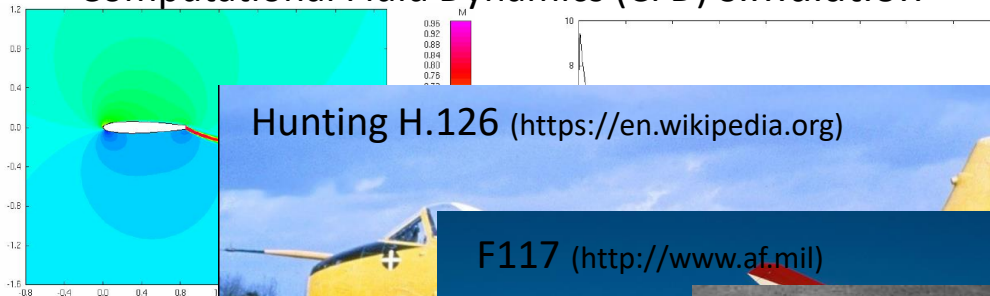
OUTLINE

1. Introduction to DEP concept
2. DEP aircraft (CTOL, STOL, & VTOL)
3. DEP/HE system research at NASA
4. Propulsion-Airframe-Integration (PAI) effects
 - Aero-propulsive coupling
 - Aircraft control
 - Noise reductions
5. R&D in electric components
6. Issues & Challenges
7. Conclusions

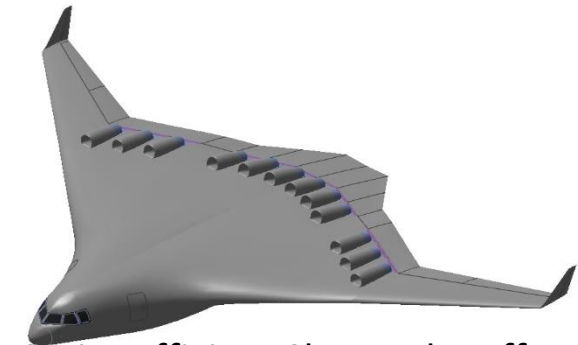
(DEP - Distributed Electric Propulsion, HE -Hybrid Electric)

- **What is Distributed Propulsion?** – No formal definition but,
- Jet flap or distributed jet from one or more engines
 - Multiple small independently powered propulsors
 - *Distributed propulsors driven by one or more power sources through various power transmission methods*

Computational Fluid Dynamics (CFD) simulation



F117 (<http://www.af.mil>)



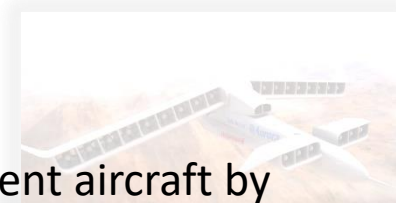
Cruise Efficient Short Take-off and Landing (CESTOL) aircraft - NASA



YB-49 (<http://www.nationalmuseum.af.mil>)

➤ **DP - Distributed propulsors driven by one or more power sources through various power transmission methods**

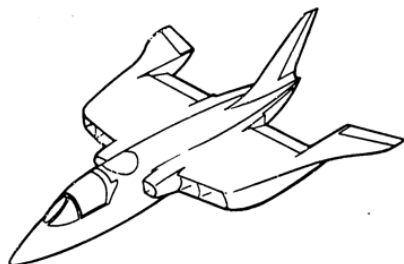
- Fluidically driven propulsor concepts
- Mechanically driven propulsor concepts
- ***Electrically driven propulsor concepts (LEAP)***



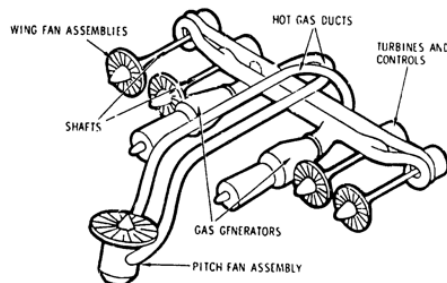
Silent aircraft by Cambridge-MIT Institute

<http://silentaircraft.org/sax40>

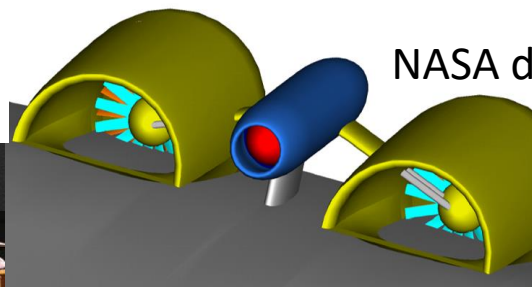
ADAM III V/STOL



Winborn, B. R. Jr., "The ADAM III V/STOL Concept," AIAA Paper 69-201



NASA dual-fan concept



Wright Flyer (<http://www.nationalmuseum.af.mil>)

➤ What is Distributed Electric Propulsion (DEP)?

- A propulsion system where electrical energy sources are connected, via transmission lines, to multiple electric motor-driven propulsors

➤ Key Features

- Power sources can be any combination of electrical power-producing devices (i.e., electric generator, fuel cell, etc.) and/or energy storage devices (i.e., battery, capacitor, etc.)
- Propulsors can be any combination of thrust producing devices such as electrically-driven propellers or fans
- Decoupled feature between the power sources and propulsive devices enables flexibility in aircraft design and efficient operation *if* efficient & compact electric machines and transmission system are employed

DEP Aircraft

Aurora eVTOL



Joby S2



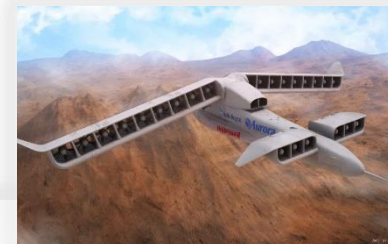
Airbus Vahana



Lilium

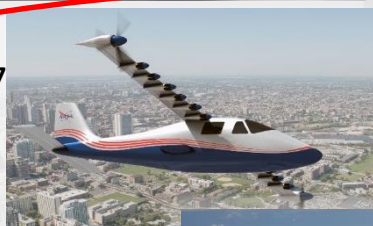


Aurora XV-24



VTOL Configurations

NASA X-57



Zunum Regional
Aircraft



ESAERO ECO-150



NASA STARC-ABL



NASA
N3-X

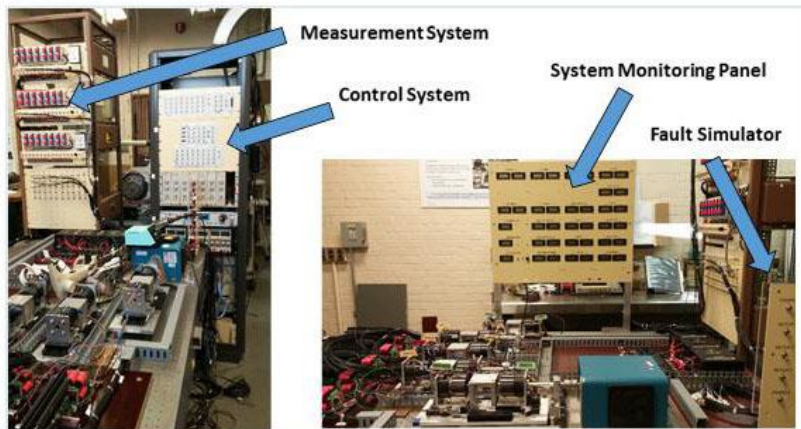
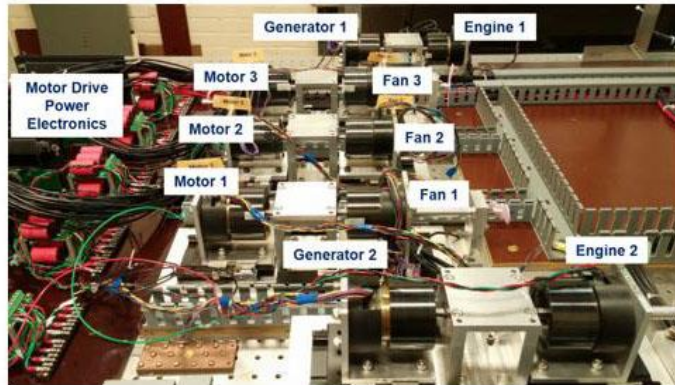


CTOL Configurations

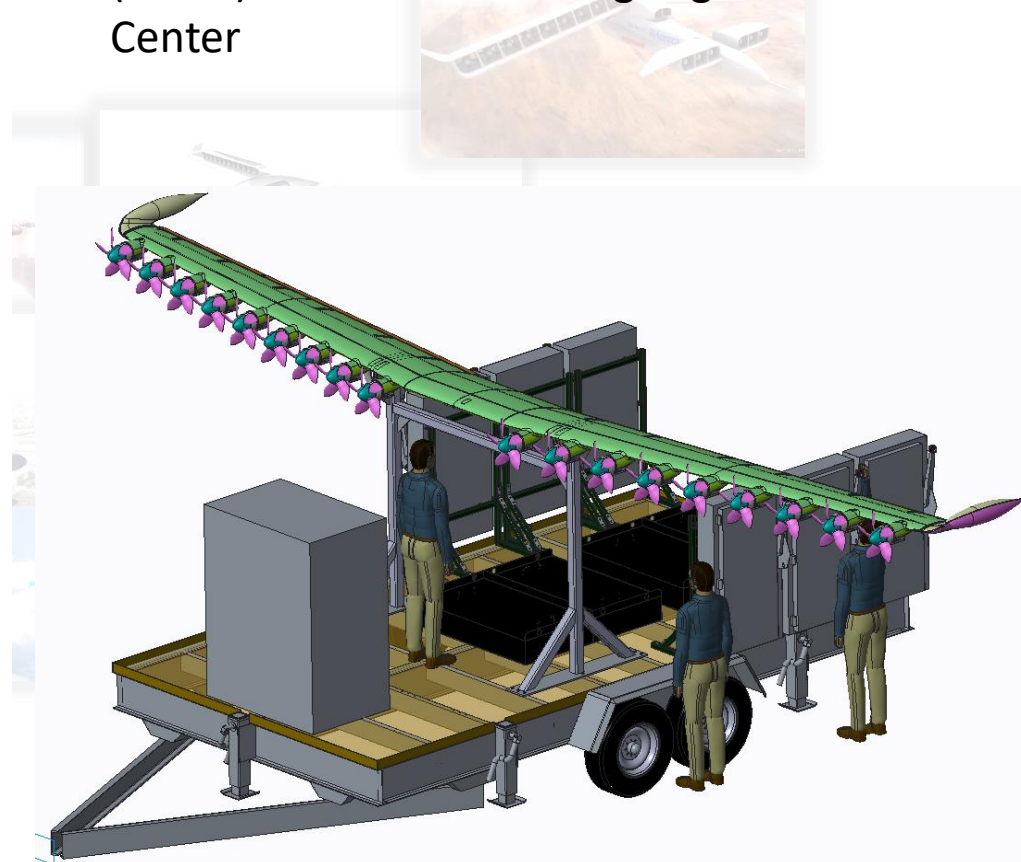
(Images used with permissions)

DEP/HE system research at NASA

Propulsion Electric Grid Simulator (PEGS)
subscale electric power system for TeDP at
NASA Glenn Research Center

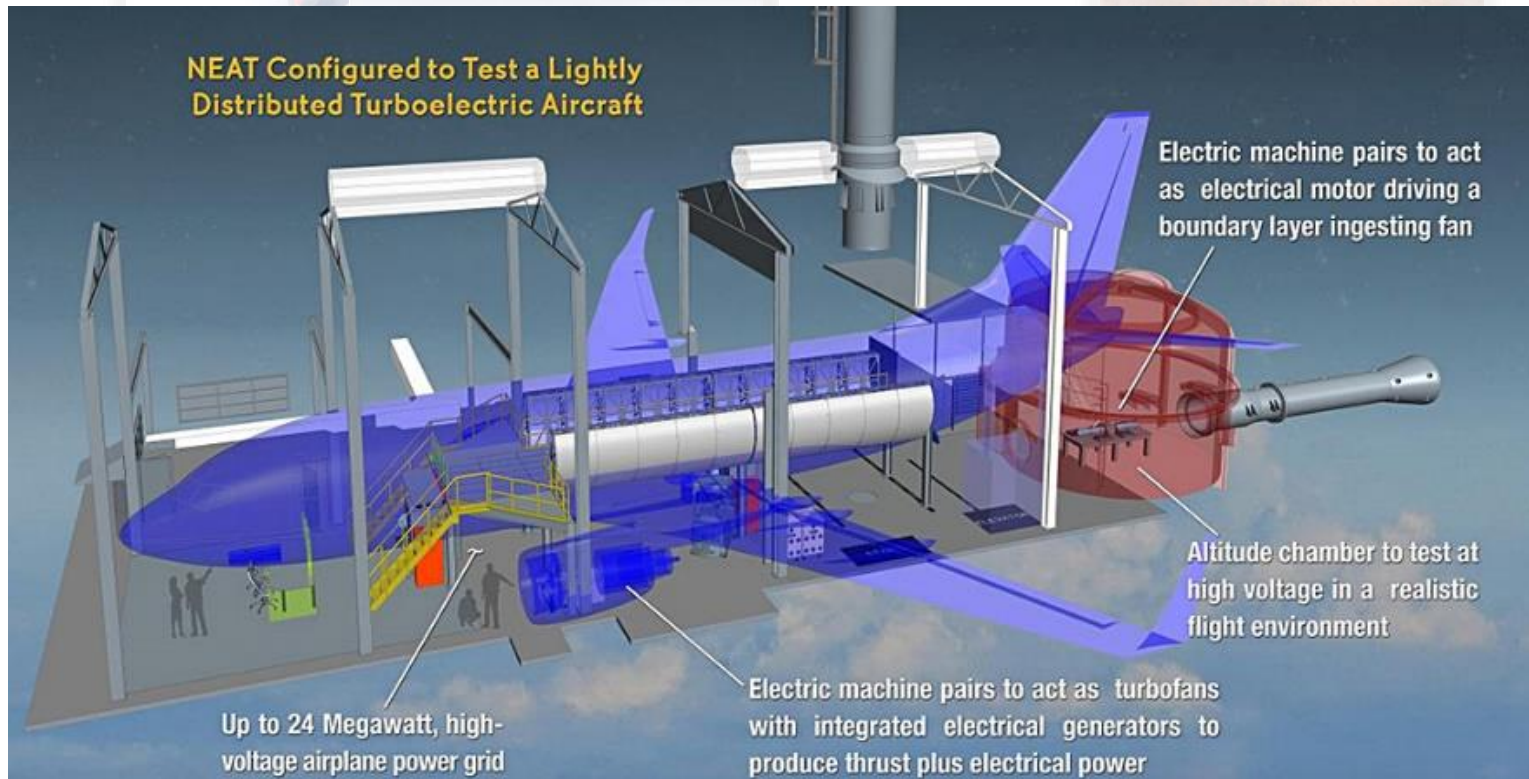


Hybrid-Electric Integrated Systems Testbed
(HEIST) at NASA Armstrong Flight Research
Center



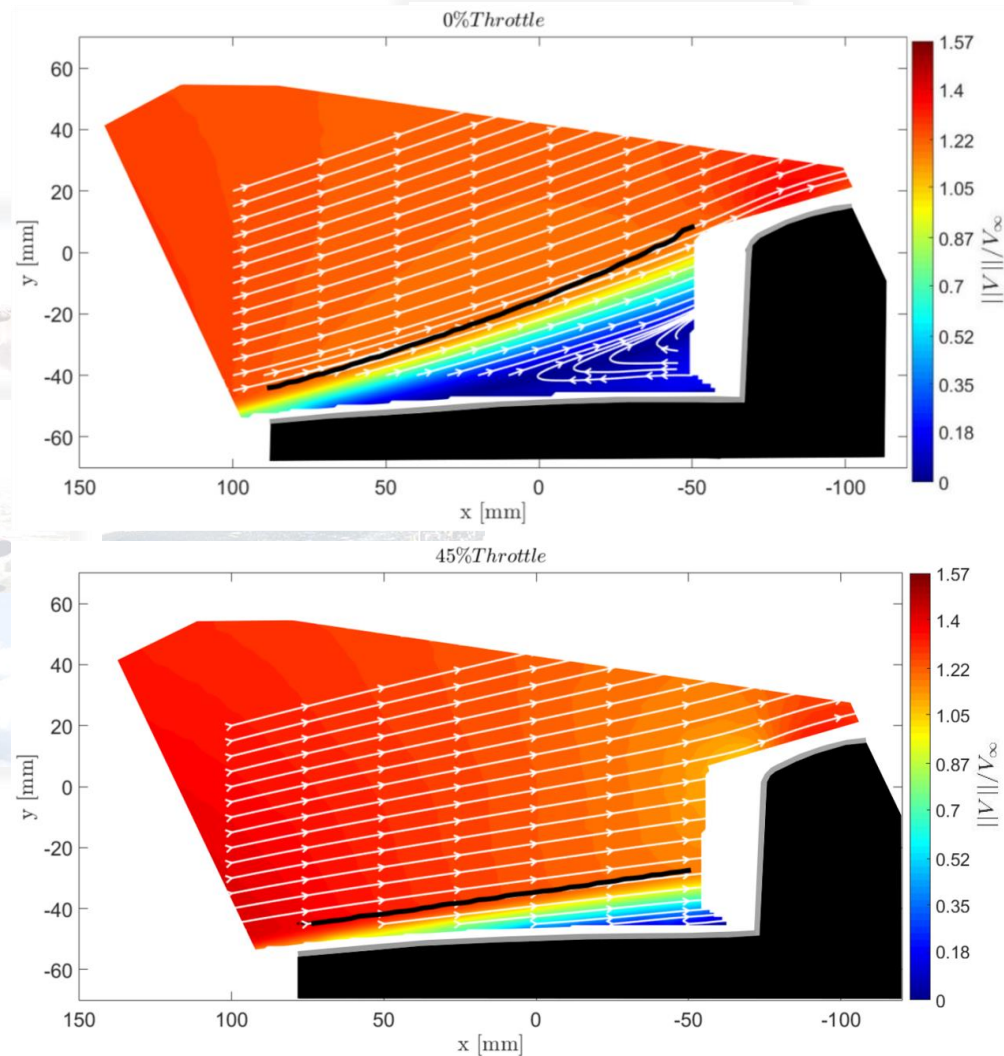
DEP/HE system research at NASA

NASA Electric Aircraft Testbed (NEAT) platform for full-scale turboelectric powertrain testing at NASA Glenn Research Center



Propulsion-Airframe-Integration (PAI) effects

- Aero-propulsive coupling
- Aircraft control
- Noise reduction



➤ Aero-propulsive coupling

- Boundary layer ingestion (BLI) benefit – increased propulsive efficiency
- Wing-tip vortex suppression and wake-filling – reduced (induced) drag
- Enhanced lift or control authority



➤ Aero-propulsive coupling

- Wing-tip vortex suppression – reduced (induced) drag



Joby S2



Airbus Vahana



NASA X-57

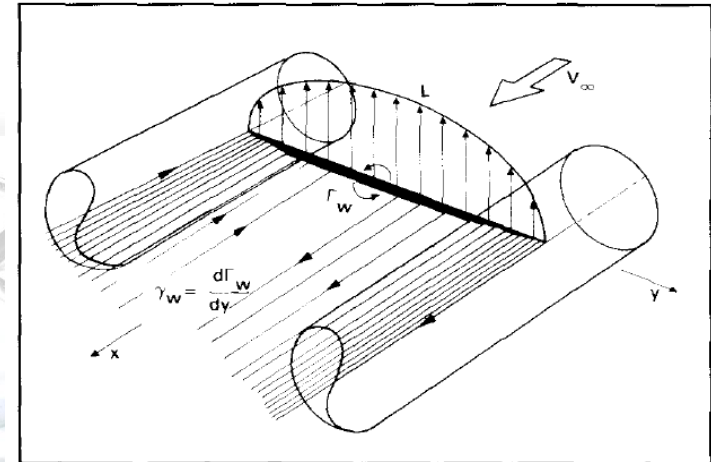
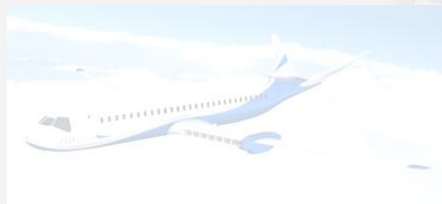


Figure 1. Vorticity Model of Wing-Propeller Combination
From Miranda, L. R. and Brennan, J. E., "Aerodynamic Effects of Wingtip-Mounted Propellers and Turbines," 1986.



➤ Aero-propulsive coupling

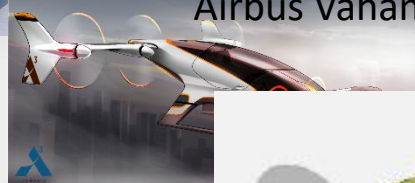
- Enhanced lift or control authority



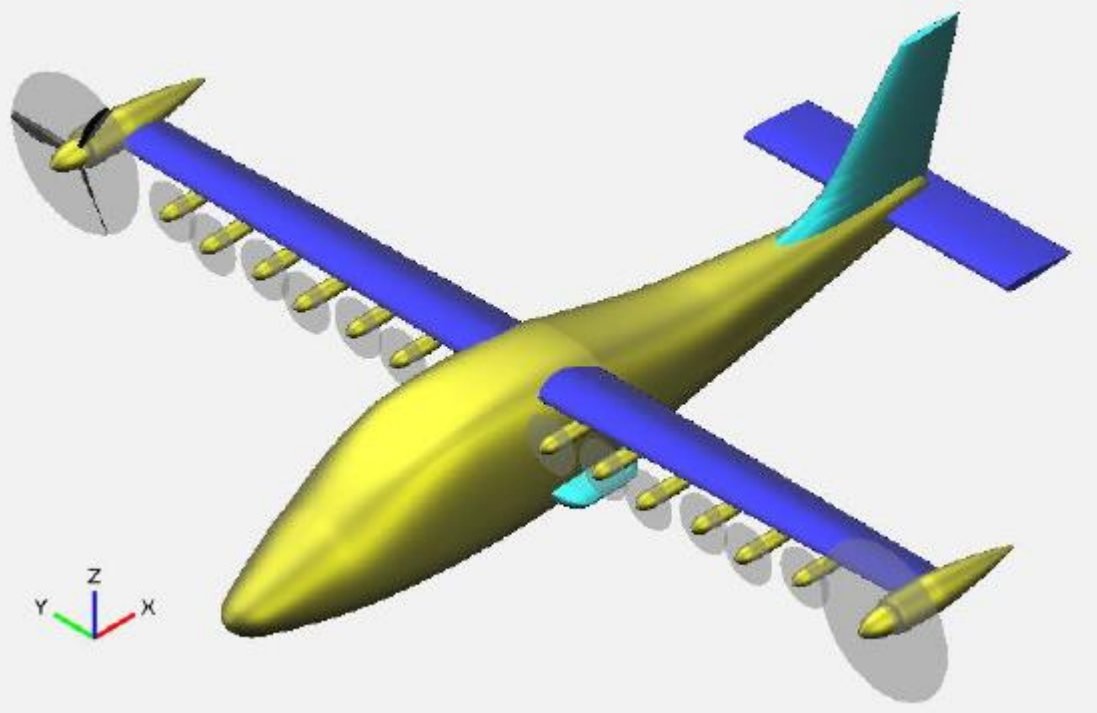
Joby S2



Airbus Vahana

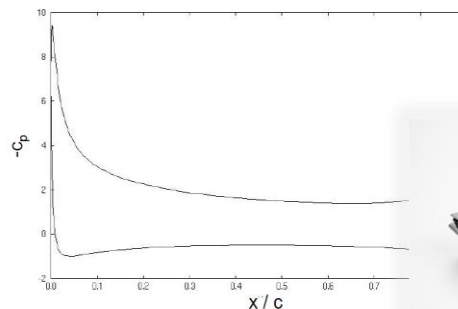
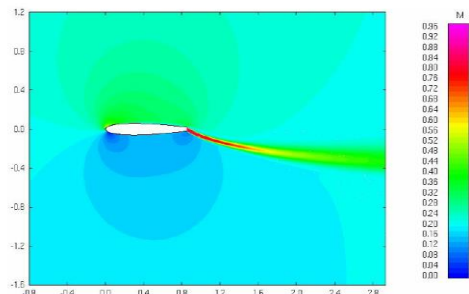


NASA X-57



➤ Aero-propulsive coupling

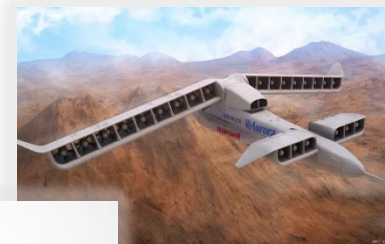
- Enhanced lift or control authority



Lilium



Aurora XV-24



ESAERO ECO-150



Hunting H.126
<https://en.wikipedia.org>

NASA
N3-X



➤ Aircraft Control

- Propulsion controlled aircraft origins (PCA)
 - 1989 DC-10 United Airlines Flight 232 accident in Sioux City, Iowa
 - Fault tolerant control (FTC)
- Initial concept challenges
 - Development of MD-11 testbed
 - Slow gas turbine response time
- The bright future
 - DEP enabled control
 - Fast electric motor response time
 - Variable pitch blades, variable area nozzles



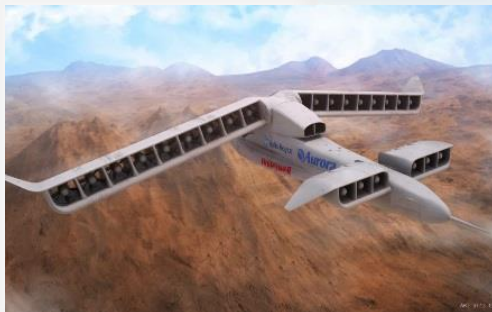
➤ DEP-based Aircraft Control

- Propulsion units as thrust-line control actuators
 - Thrust vectoring (Lilium)
- Enhanced control authority from blown surfaces
- Improved control redundancy/robustness to vehicle damage
- Reduction/elimination of traditional stabilizer/control surfaces
- Propulsion induced aeroelastic responses

Lilium

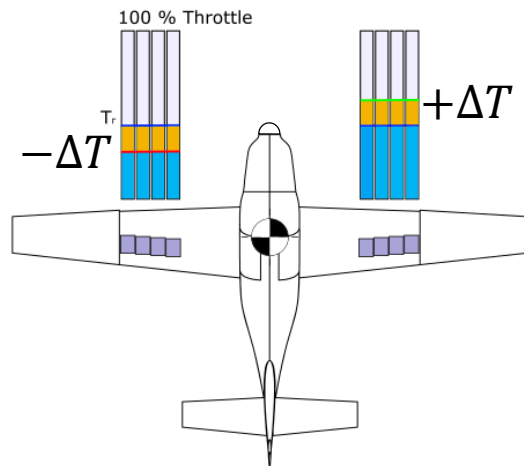


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➤ DEP-based Aircraft Control

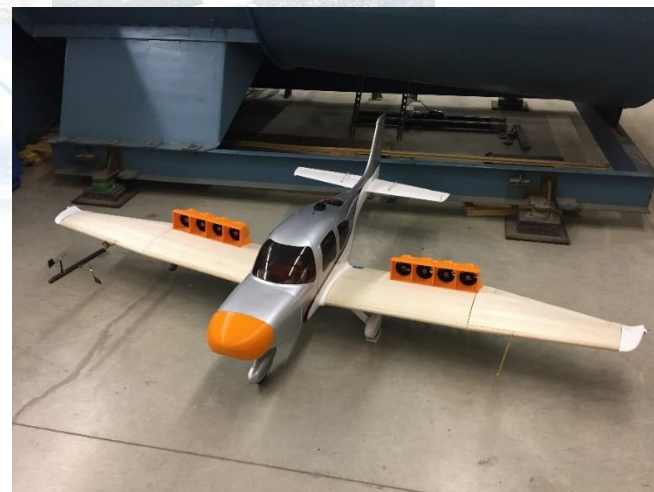
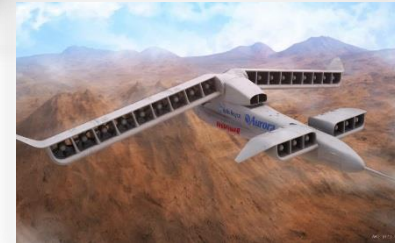
- Several concepts exhibit DEP control
 - Thorough system identification tests for controller development (GL-10)
- Ongoing research at UIUC
 - Scaled Cirrus SR22 DEP variant
 - Flight tests – influence of propulsors on dynamics
 - Compare to baseline



Lilium



Aurora XV-24



➤ Noise Reductions

- NASA Chapter 4 far term noise goal: cumulative margin 52EPNdB
- High effective bypass ratio for low FPR (N3-X margin of 32EPNdB)
- Shielding propulsion units from ground (N3-X margin of 64EPNdB)
- Electric machine noise
- X-57 Acoustic studies



R&D in electric components

➤ Current capabilities

- Applicable to general aviation aircraft and UAVs

➤ Areas of research

- Megawatt scale electrical machines (UIUC)
- Hybrid electric systems
- Power transmission architectures for DEP
- Inverters, converters, power transmission

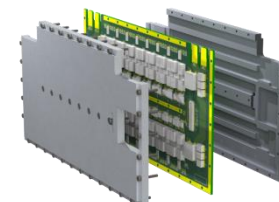


Table 1 Current electrical component capabilities for aircraft applications.

Motor Power Capability (MW)	Motor Specific Power (kW/kg)	Electronics Power Capability (MW)	Electronics Specific Power (kW/kg)	Battery Specific Energy (Wh/kg)
0.25	2.2	0.25	2.2	200-250

Issues & Challenges

- Inlet distortion from BLI (NASA GRC tests)
- Electrical component technology readiness
 - Weight, power ratings, certification, energy density
- Noise generation for eVTOL in urban environment
- Loss of propulsion units used for control/lift augmentation
 - Must be able to take off and land
 - Must be able to control vehicle



Conclusions

➤ Distributed Electric Propulsion

- Electrical energy sources are connected to multiple electric motor-driven propulsors
- Mechanical decoupling of power production and propulsive power expenditure
- Use across CTOL, STOL, VTOL

➤ Advantages

- Improved efficiency and performance
- DEP-enabled vehicle control
- Reduced operational noise

➤ Electrical Systems Research Thrusts

- Components: motors, drives, electronics, energy storage
- Power distribution architectures
- System performance and control

➤ Challenges for Future Study

- Inlet distortion
- Redundancy and fault tolerance
- Impact of VTOL and increased vehicle traffic on community noise
- Battery systems and electrical components